

Determining the Characteristics and Mechanisms for Biological Clutter and Environmental Reverberation and their Impact on Long Range Sonar Performance in Range-Dependent Fluctuating Ocean Waveguides

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LONG-TERM GOALS AND OBJECTIVES

Determine the temporal and spatial characteristics, and physical mechanisms for biological clutter and environmental reverberation in long-range wide area active sonar systems. This understanding is used to develop operational and signal processing techniques to distinguish biological clutter from scattered returns due to man-made targets, and to determine the limits placed by environmental reverberation on target detection. In the second area, the statistical properties of broadband acoustic signals transmitted and scattered in range-dependent ocean waveguides is examined. This knowledge is then used to determine the extent to which environmental variabilities limit our ability to perform target localization and parameter estimation through beamforming and match-filtering broadband data from active sonars in fluctuating and dispersive ocean waveguides.

APPROACH

The research effort involves developing and enhancing physics-based theoretical models for coherent and incoherent scattering from groups of fish and other biological organisms, multi-static scattering from extended targets, and environmental reverberation in *range-dependent* ocean waveguides. The vast amounts of data collected during the ONR-sponsored acoustic experiments in the Gulf of Maine in 2006 and on the New Jersey Strataform in 2003 with long-range sonar systems are processed and analyzed.

WORK COMPLETED AND RESULTS

1. Processing and Analysis of 2006 OAWRS Experiment Data from the Gulf of Maine

During the ONR-Sloan Foundation sponsored acoustic experiment in the Gulf of Maine in Sep-Oct 2006, both massive shoals and small discrete schools of fish were imaged near Georges Bank with the long range wide-area sonar system, OAWRS (Ocean Acoustics Waveguide Remote Sensing) [1,2]. OAWRS uses low frequency acoustic signals in the 300 Hz to 1.5 kHz frequency range to enable instantaneous continental shelf scale imaging of fish and other objects in the ocean waveguide that is unaliased in space. Concurrent measurements were made using conventional fish-finding sonars (CFFS), the Simrad EK60 (38 kHz) echosounder and the Reson 7125 (400 kHz) multibeam sonar. Trawl surveys conducted during the experiment identified Atlantic herring as the dominant species of fish (over 99%) imaged along with a small fraction of redfish and haddock.

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- *Co-registration and correlation of OAWRS and EK60 echosounder data*

High spatial-temporal correlation is found between prominent scattered returns observed in OAWRS imagery with fish locations in the line-transect measurement of the CFFS over the two week period of the experiment. Movies have been made concatenating consecutive OAWRS images that also show the corresponding instantaneous point location of the CFFS system and the depth dependence of fish along the line transect of the CFFS.

- *Estimate scattering strength of fish imaged with OAWRS*

An approach has been developed and applied to convert OAWRS pressure-squared level images to scattering strength (SS) level images in areas with high concentrations of fish. The expected transmission loss from source and receiver to fish locations in the highly range-dependent and random Georges Bank environment is modeled with an empirical approach that employs the parabolic equation (PE) model, RAM (see subsection 4). The OAWRS pressure-squared level images are corrected for this two-way transmission loss, source level, and the spatially varying resolution footprint of the OAWRS system to provide estimates of SS levels at fish pixels. The inversion procedure takes into account variations in the expected incident intensity as a function of target depth caused by a refracting, non-uniform water-column sound speed profile.

Scattering strength has units of a pure dB and is a very useful quantity for comparing scattering from different regions of the ocean, for both near and distant scatterers [1,3,4]. This is because the range-dependent geometric spreading and absorption losses present in the raw images have been corrected for. At fish locations, SS can be expressed as a function of fish expected individual target strength and the local fish density.

- *Examine the resonance scattering mechanism of Atlantic herring as a function of frequency*

The intensity of scattered returns from fish groups imaged in the Gulf of Maine is strongly dependent on the acoustic frequency of the OAWRS system. Some fish were found to return higher scattered fields at around 400 Hz than at an octave higher at roughly 1 kHz. The herring for instance gave stronger returns at 1 kHz than they did at 415 Hz in general. The herring possess swimbladders that scatter low frequency sound waves like damped air-bubbles and exhibit resonance frequencies for scattering. Their resonance frequencies depend on the volume of air enclosed by their swimbladders, and has been measured by different investigators in the Gulf of Maine area to range from 2.5 kHz to 5 kHz [5,6].

Here our analysis shows that scattering strength of herring increases with OAWRS operating frequency from 400 Hz to 1.2 kHz. It is about 20 dB higher at 1 kHz than at 415 Hz, as shown in Fig 1.

- *Future Work: Target strength and abundance estimation, and study spatial-temporal behaviour of herring shoals*

We are in the process of calibrating the expected target strength of herring as a function of OAWRS imaging frequency by comparing CFFS estimates of fish density with OAWRS scattering strength imagery. A theoretical physics-based model for scattering from fish groups that takes into account both coherent and incoherent scattering effects (refer to section 2) are being applied to these data sets to provide a calibration for the OAWRS system and to derive estimates of aerial fish population densities. Current estimates of the Georges Bank Atlantic herring stock stands at around 10 to 15 billion individuals based on fisherman catches and NEFSC-NOAA annual herring echosounder and trawl surveys [7]. Estimates will be provided of the abundance of the Atlantic herring population based on OAWRS. These results will be applied to study the migration and spawning behavior of

herring shoals over the entire Georges Bank over several diurnal periods. From the Navy perspective, the minimum aerial density of herring needed to cause biological clutter will also be determined. An understanding of the temporal-spatial behaviour of these fish groups will then be used to derive operational cues to distinguish biological clutter from returns due to man-made targets.

2. Develop theoretical models for scattered fields from fish groups and output after match-filtering and beamforming

Both analytic and computational models for scattering from a random distribution of fish of random sizes are currently under development. At the low acoustic frequencies used in OAWRS of several hundred Hz to a few kHz, most fish are compact scatterers and their scattered fields can be modeled using the sonar equation. The scattered field expressions are matched-filtered with the source signal and beamformed to determine the contribution from fish within the OAWRS resolution footprint. Statistical moments of the resultant fields are then calculated to determine the level of coherent and incoherent contribution to the total scattered intensity. When coherent scattering dominates, the far-field scattered levels are proportional to N^2 , where N is the number of fish in the group within the sonar resolution footprint. When incoherent scattering dominates, the scattered levels are proportional to N .

These expressions are being verified with Monte-Carlo simulations of the scattered fields from fish groups in an ocean waveguide. Preliminary analysis with the models indicates that the relative level of coherent to incoherent intensity depends on the density and size of the fish group as well as their spatial distribution functions.

3. Developing calibrated, unified, analytic and numerical volume scattering, rough surface scattering, and Lambertian scattering models for sea bottom reverberation in range-dependent and fluctuating ocean waveguides.

An analytic model has been developed for scattering from random volume inhomogeneities in *range-dependent* ocean waveguides using the Rayleigh-Born approximation to Green's theorem [3]. The expected scattered intensity depends on statistical moments of fractional changes in compressibility and density, which scatter as monopoles and dipoles respectively, and the coherence volume of the inhomogeneities. The model is calibrated for ocean bottom scattering using data acquired with OAWRS and geophysical surveys of the ONR Geoclutter Program [1]. The scattering strength of the seafloor on the New Jersey shelf, a typical continental shelf environment, is found to depend on wavenumber, medium coherence volume and seabed depth penetration factor [3].

A computationally efficient numerical approach is also developed to rapidly compute bottom reverberation over wide areas using the parabolic equation by exploiting correlation between monopole and dipole scattering terms and introducing seafloor depth penetration factors. Without innovations of this kind, bottom reverberation models based on volume scattering can be computationally intensive in range-dependent environments with bistatic source-receiver geometries because dipole scattering involves multi-dimensional spatial derivatives of the complex waveguide Green function. These typically must be computed numerically using large and dense 3D matrices. We will now apply this volume scattering model to study seafloor reverberation in the Gulf of Maine during the OAWRS 2006 experiment. Reverberation data over a three octave frequency band from 300 Hz to 1.2 kHz measured concurrently will be analyzed with the model to further examine and quantify the frequency dependence of seafloor scattering.

The next step is to develop models for sea bottom reverberation based on other scattering mechanisms, such as rough surface scattering and as an empirical Lambertian surface. These mechanisms have been previously modeled using a normal-mode formulation for stratified and range-independent ocean waveguides [8,9]. Here, we will develop corresponding formulation that is applicable to range-dependent waveguides with varying bathymetry in terms of the waveguide Green function which will be implemented using RAM. The rough seafloor scattering model will be developed by applying Kirchhoff's approximation to Green's theorem. The statistical parameters of the rough surface such as the roughness height standard deviation and correlation lengths, or alternatively, the roughness height wavenumber spectrum will be incorporated into the model. The Lambertian bottom scattering model will include an albedo [8,9] for surface absorption losses to be obtained by calibration with reverberation data. The eventual goal is to compare all three mechanisms for bottom scattering and determine the mechanism that best explains the observed OAWRS data as a function of acoustic frequency and range from the sonar system.

4. Broadband transmission statistics, match-filter degradation and empirical model for expected intensity

The mean and standard deviation of broadband signals transmitted through the random range-dependent New Jersey continental shelf environment have been quantified [10]. The broadband data comprise of linear frequency modulated pulses with bandwidths of between 50 to 150 Hz in the 300 Hz to 1.5 kHz frequency range transmitted from a vertical source array and received using a horizontally towed array. The data are obtained from the ONR sponsored 2003 Main Acoustics Experiment of the Geoclutter Program. The signal Parseval sum and match filtered pressure squared levels are found to have a significantly smaller standard deviation of about 3 to 3.5 dB compared to the instantaneous center frequency equivalent of about 5 dB. These statistics indicate that the number of independent fluctuations over the received signal duration is roughly 2 resulting in a coherence bandwidth of about 25 Hz. The match filter degradation caused by modal dispersion in the ocean waveguide is quantified and can be decomposed into two parts, an initial offset at the onset of modes, and a decay that accumulates with range. These effects have been accounted for using Monte-Carlo simulations in an ocean waveguide randomized by internal wave fields with the typical temporal and spatial correlation scales observed in shallow waters.

An empirical model is developed for rapidly estimating the expected acoustic intensity transmitted in a range-dependent waveguide using the parabolic equation model [10]. The range-dependent acoustic model RAM takes into account parameters of the ocean environment such as the sound speed profile, the geo-acoustic parameters of the seafloor, and the varying bathymetry over range. It is unrealistic to be able to account for all environmental parameters that contribute to the transmission loss. For this reason an attenuation coefficient correction is introduced to account for an overestimation or underestimation of the absorption and scattering losses in the water column and seabed. The model is calibrated for the New Jersey continental shelf using both the Parseval sum and match-filtered measurements as shown in Fig. 1. An advantage of this empirical model is that we avoid the need for Monte-Carlo simulations, which require detailed knowledge of the statistical properties of the physical processes that randomize the waveguide. This empirical model can be applied to sonar imagery to efficiently estimate the expected intensity incident on a target to rapidly invert the scattered intensity for target strength.

5. Develop scattering model for vertically extended targets in range-dependent waveguides with varying sound speed profile.

The objective here is to derive and develop a model for scattering off of a vertically extended target for *range-dependent* shallow water waveguides with substantial sound speed change over the target depth. For vertically extended pressure-release or rigid targets, the scattered field is formulated using Green's theorem to satisfy the boundary conditions at each depth of the target. This model is implemented numerically in a *range-dependent* waveguide by first determining the incident field on the boundary of the target. The locally scattered fields on the target surface are estimated using Kirchhoff's approximation to Green's theorem. The scattered field from the target in the far-field is then estimated by propagating the locally scattered fields at each depth of the target in the range-dependent waveguide and coherently summing these at the location of the receiver. For vertically extended objects with small density and sound speed contrasts, the Rayleigh-Born approximation to Green's theorem is used to derive their scattered fields. The object's vertical extent is then no longer limited to an iso-speed layer, but can span over depth with changes in the sound speed structure. The vertically extended BBN targets were deployed during experiments in the New Jersey shelf and in the Gulf of Maine to enable accurate geographic charting of long range sonar imagery. The model developed here will be calibrated with scattered field data from the BBN targets in these experiments.

The same approach is also being applied to model and study seismic wave scattering from extended air-filled tunnels buried underneath the ground. The ground is considered as an isotropic elastic medium that can excite both compressional and shear waves. Here care must be taken on correctly treating the coupling of energy between these two types of waves, which travel at different speeds depending on the ground properties and stratification. Numerical implementation of the method is done by using the parabolic equation (PE) model for elastic media [11]. The elastic PE can correctly treat range-dependent elastic layers, and the coupling between the compressional and shear wave fields. The incident field at the target is calculated in terms of the horizontal (u) and vertical (w) displacements that are then used for calculating the scattered field and the reverberation from surrounding medium heterogeneities. The project aims at identifying the range thresholds for tunnel detection above ambient noise and medium reverberation, as a function of the frequency of the seismic waves, the tunnel dimensions, the receiver array geometry and the medium properties. Also, because the elastic PE can model both compressional and shear waves as well as interface waves, the most suitable wave type for detection purposes will be identified.

IMPACT/APPLICATIONS

We have demonstrated that the dominant source of both target and non-target like clutter that can either confuse or camouflage returns from an underwater vehicle in general continental shelf areas is fish.

RELATED PROJECTS

Research on several of the areas listed above are being conducted in collaboration with Nick Makris and his team at MIT and J. Michael Jech of NEFSC-NOAA. The results of this research also supports the National Oceanographic and Partnership Program (NOPP) on fish sensing and imaging.

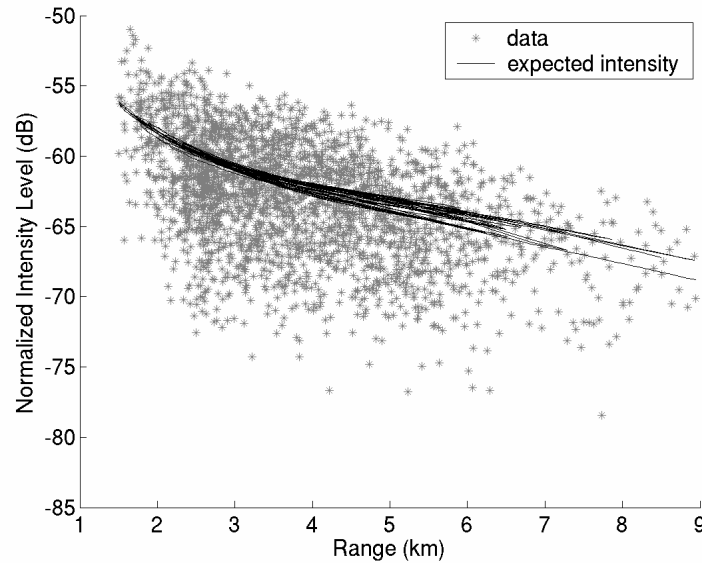


Figure 1: Intensity of 1s LFM chirp pulses from 390 to 440 Hz propagated from a stationary source to a receiver moving at 2 m/s through the ocean waveguide on the New Jersey Strataform. The empirical model for expected intensity calibrated against the data. Figure taken from Ref. 10.

PUBLICATIONS AND REFERENCES

- [1] N.C. Makris, P. Ratilal, D.T. Symonds, S. Jagannathan, S. Lee, and R. Nero, "Fish Population and Behavior Revealed by Instantaneous Continental-Shelf-Scale Imaging," *Science*, Feb. (2006).
- [2] P. Ratilal, Y. Lai, D. Symonds, L. Ruhlmann, J. Preston, E. Scheer, M. Garr, C. Holland, J. Goff, and N. Makris "Long range acoustic imaging of the continental shelf environment: The Acoustic Clutter Reconnaissance Experiment 2001," *J. Acoust. Soc. Am.* 117, 1977 (2005).
- [3] A. Galinde, N. Donabed, S. Lee, N.C. Makris and P. Ratilal, "Range-dependent waveguide scattering model calibrated for bottom reverberation in continental shelf environments," submitted to *J. Acoust. Soc. Am.*, (2007).
- [4] N. Donabed, "Development of a Calibrated Bistatic Rayleigh-Born Bottom Reverberation Model for Range-Dependent Continental Shelf Environments," Northeastern Univ. Master's Thesis, Ratilal advisor, (2006).
- [5] R.W. Nero, C.H. Thompson, J.M. Jech, "In situ acoustics estimates of the swimbladder volume of Atlantic herring (*Clupea harengus*)," *ICES J. Mar. Sci.*, Vol. 61, 323-337 (2004).
- [6] T. Stanton, D. Chu, J.M. Jech, J.D. Irish, "A broadband acoustic system for resonance classification of swimbladder-bearing fish," *J. Acoust. Soc. Am.*, Vol. 120, 3000, (2006).
- [7] W.J. Overholtz, J.M. Jech, W.L. Michaels, and L.D. Jacobson, "Empirical comparisons of survey designs in acoustics surveys of Maine-Georges Bank Atlantic Herring," *J. Northw. Atl. Fish. Sci.*, Vol. 36, 127-114, (2006).

- [8] N. C. Makris and P. Ratilal, "A unified model for reverberation and submerged object scattering in a stratified ocean waveguide," *J. Acoust. Soc. Am.*, Vol. 108, 909-941 (2001).
- [9] P. Ratilal, "Remote sensing of submerged objects and geomorphology in continental shelf waters with acoustic waveguide scattering," Ph.D Thesis, MIT (2002).
- [10] M. Andrews, T. Chen, S. Lee, N.C. Makris, and P. Ratilal, "Broadband transmission statistics and match filter degradation in the New Jersey Continental shelf," to be submitted to *J. Acoust. Soc. Am.* in Oct. 2007.
- [11] E. T. Kusel, W. L. Siegmann, M.D. Collins, "A single-scattering correction for large contrasts in elastic layers," *J. Acoust. Soc. Am.*, Vol. 121, 808-813, (2007).

HONORS/AWARDS/PRIZES

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